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MODEL MX-1593

REPORT ZM-7-007

DATE October 4, 1951

[redacted]

AD847789

TITLE

REPORT ZM-7-007

TACTICAL BALLISTIC MISSILE STUDY -

ROCKET ENGINE SWIVELING REQUIREMENTS

Classification Changed To: UNCLASSIFIED
Authorized by: DD 254 / SSCG Date 5/07A Dep 20-1
Reclassified By: Richard J. Cook Date 3-6

DDC
FEB 13 1969

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GROUP MX-1593

REFERENCE

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TACTICAL BALLISTIC MISSILE STUDY - ROCKET ENGINE SWIVELING REQUIREMENTS

I OBJECT

To determine the hydraulic system requirements for swiveling the second stage rocket engines (thrust, 44,250 lbs.) of the 5500 nautical mile ballistic missile. The torque requirements for swiveling the rocket engines and the estimated weights of the hydraulic system components are included in this study.

II SUMMARY

In order to more fully justify the hydraulic system weights presented in the MX-1593 Interim Summary Report ZM-7-001, the following analysis has been prepared.

The configuration, size and weight of the rocket engine used in these calculations are based upon the design studies presented in the Report ZM-7-001. These data have been discussed with Aerojet Engineering Corporation and is in close agreement with their findings and, therefore, considered to be reasonably accurate.

The hydraulic system for actuating the rocket engines is illustrated in Figure II. This system consists of one (1) New York Air Brake Model 67W variable delivery pump supplying hydraulic power to a hydraulic cylinder and servo valve on each of the four (4) rocket engines. The hydraulic pump is gear driven from a second stage turbo pump and has a maximum delivery of 27.5 gal/min. at 2500 psi. In order to reduce the hydraulic oil temperature, a liquid to liquid heat exchanger is used. The high circulation rate and heat rejection of the Model 67W pump make this necessary as the pump heat rejection at zero flow and 3000 psi is approximately 210 BTU/min. The heat exchanger will be small since the gasoline (coolant) flow rate to each rocket engine is 77.6 gal/min. as compared to the maximum flow of 27.5 gallons per minute for the hydraulic pump. A 60 cu. in. accumulator is contained in the system to smooth out the pressure impulses and to satisfy the high instantaneous flow demands. Since this pump contains integral variable delivery and pressure regulating features, separate valves and controls will not be required.

The control system weight of 140.8 lbs. as shown in the summary table is in close agreement with the estimated weight of 140 lbs. as noted in the Interim Summary report ZM-7-001. This control system as shown in Figure I, Rocket Engine Swiveling Force, has sufficient available torque for accelerations of more than $1000^\circ/\text{sec}^2$ which is estimated to adequately control the missile where the rocket engine swiveling angle does not exceed $\pm 10^\circ$. The hydraulic cylinder size for this application has a nominal inside diameter of 1.46 inches and a stroke of 4.25 inches. The weight of this cylinder from Figure IV is approximately 2.71 lbs. However, this weight is for a 1500 psi system pressure and is increased here by a factor of 1.5 so the weight used here is 4.0 lbs. ($2.71 \times 1.5 \cong 4.0$) for a cylinder with 3000 psi system pressure.

III DESIGN ANALYSIS

a. Force required for a constant angular velocity of the swiveling rocket engine.

$$\text{Torque, ft. lbs.} = R^2 \; m \left[V - V_e \right] A_e \, \omega$$

R = distance from swiveling point to rocket nozzle exit, ft.

V = missile velocity, ft/sec.

V_e = propellant nozzle exit velocity, ft/sec.

A_e = nozzle area, sq. ft.

ω = angular velocity of rocket engine, radians/sec.

m = $\frac{W}{g}$, propellant gas density, $\frac{\#/\text{cu.ft.}}{g}$

Torque required for an angular velocity of one radian per second (95.6 rpm)

$$T = \left(\frac{82.5}{12}\right)^2 \times \frac{.00201}{g} \left[22,900-10,300\right] \quad 1.73^2 \pi \times 1$$

$$= 348.0'\#$$

$$\text{H.P.} = \frac{95.6 \times 348}{5250} = 6.34$$

b. Force required to accelerate swiveling rocket engine.

$$\text{Torque, ft. lbs.} = \frac{W}{g} r_o^2 \quad 2\pi \quad a_r$$

W = weight of rocket engine, lbs.

r_o = radius of gyration of rocket engine

a_r = acceleration of rocket engine about swiveling axis, rev./sec.^{2}

Instantaneous torque required for an acceleration of 1000°/sec.^{2}

I_1 = moment of inertia about swiveling axis = 220.86 slug ft.^{2}

$$I_1 = m r_o^2$$

$$r_o = \sqrt{\frac{I}{m}} = \frac{220.86}{9.95} = 4.71 \text{ ft.}$$

$T = 9.95 \times 4.71^2 \times 2 \times 2.78 = 3,862\text{'}\#$

c. Rocket Engine - Moment of Inertia Calculation

The moment of inertia calculation is based upon the engine configuration shown in Figure III. These calculations are dependent upon the following assumptions:

Thrust = 44,250 lbs.

L_*, (characteristic length) $= \frac{\text{chamber volume}}{\text{throat area}} = 40$

λ_c, chamber length $= L_* \left(\frac{d_t}{d_c}\right)^2$

d_t, throat dia.

d_c, chamber dia.

P_c, chamber pressure = 500 psia

ϵ, area ratio-throat to nozzle = 20

$T = C_F P_c A_t$

$A_t = \frac{44,250}{1.34 \times 500} = 67.6$ sq. in., $d_t = 9.28$" dia.

$A_e = 67.6 \times 20 = 1352$ sq. in., $d_e = 41.50$" dia.

t_o = outer engine wall thickness = .040 in.

t_i = inner engine wall thickness = .032

MOMENT OF INERTIA SUMMARY - ROCKET ENGINE

Item	$\frac{m}{g}$	I slug ft.^{2}	a* ft.	m a	m a^2	I_A
Nozzle	6.321	67.92	4.84	30.6	148.0	215.92
Combustion Chamber Cyl.	.916	.985	.904	.829	.748	1.733
Combustion Chamber Cone	.579	.362	1.776	1.029	1.825	2.187
Injector	1.830	.275	.638	1.168	.744	1.019
Total	9.94			33.62		220.86

$I_A = I + ma^2$

$\Sigma I_A = I + \Sigma ma^2$

$I = 220.86 - (9.94 \times 3.38^2) = 107.26$ slug ft^2

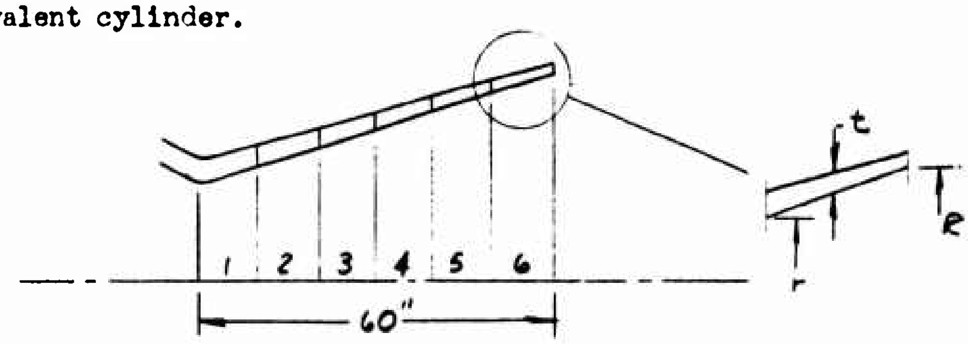
a*, distance to engine swivel point

ROCKET ENGINE WEIGHT SUMMARY

Item	Weight-Lbs.
Nozzle outer shell	128
Nozzle inner shell	68
Combustion chamber outer shell	20.5
Combustion chamber inner shell	7.7
Injector	59
Residual fuel	38
Total Weight	321.2

MOMENT OF INERTIA CALCULATION - ENGINE NOZZLE

The moment of inertia of the nozzle is determined by dividing the nozzle length into six sections and calculating the I of each section as an equivalent cylinder.



Zone	r in.	R in.	Area Sq. In.	W-# Structure	W-# Fuel	W_T	t in.
1	4.64	7.32	375	14.5	3.17	17.67	.326
2	7.32	10.0	544	21.05	3.17	24.22	.224
3	10.0	12.68	712	27.55	3.17	30.72	.169
4	12.68	15.26	877	33.90	3.17	37.07	.139
5	15.26	18.04	1045	40.4	3.17	43.57	.117
6	18.04	20.72	1217	47.1	3.17	50.27	.1002
			4770 sq. in.	184.5#		203.5#	

Area = $\pi s \; (R + r)$

Volume of fuel per section = 3.17/.026 = 122 cu. in.

t, equivalent distance between inner and outer shell

MOMENT OF INERTIA - ENGINE NOZZLE

Zone	R_1 ft.	r_1 ft.	m	I slug ft^2	a* ft	ma^2	ma	I_A
1	.532	.498	.548	4.64	4.59	11.55	2.51	16.15
2	.746	.722	.754	6.48	3.75	10.6	2.82	17.08
3	.964	.945	.954	8.37	2.92	8.12	2.78	16.49
4	1.186	1.168	1.151	10.40	2.08	4.98	2.39	15.38
5	1.396	1.382	1.352	12.57	1.25	2.11	1.69	14.68
6	1.629	1.612	1.562	15.07	.416	.270	.649	15.34
			6.32	57.53			12.86	94.12

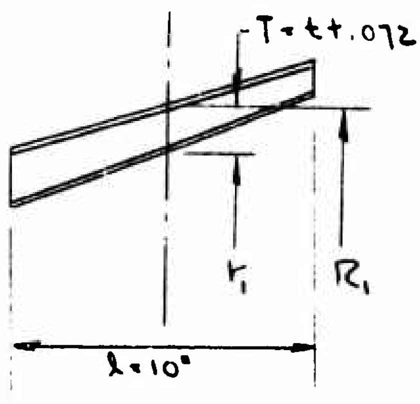
a* distance to nozzle exit

C.G. location = 12.86/6.32 = 2.03 ft. from nozzle exit

$$\Sigma I_A = I + \Sigma ma^2$$

$$I = 94.12 - (6.32 \times 2.03^2) = 67.92 \text{ slug ft.}^2$$

$$I = m\left(\frac{l^2}{3} + \frac{R^2 + r^2}{4}\right)$$



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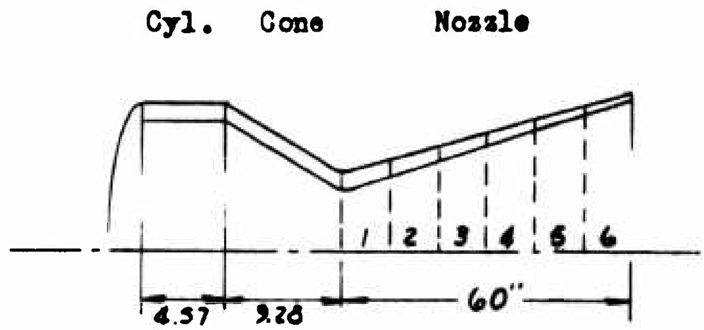
MOMENT OF INERTIA - COMBUSTION CHAMBER



Item	W_T-lbs.	Cyl.-wt.	Cone wt.
Outer Shell	20.5	12.38	8.12
Inner Shell	7.7	4.7	3.0
Fuel	19	11.48	7.52
Total	47.2	28.56	18.64

Truncated cone area $= \pi S \ (R + r)$

$= \pi \ 10.38 \ (9.28 + 4.64)$

$= 454^{\square''}$

Cylinder area $= 18.56 \times 4.57 = 266.5^{\square''}$

Fuel volume - gasoline density $= 44.9/1728 = .026$#/cu. in.

cylinder 11.48/.026 = 441 cu. in.
cone 7.52/.026 = 289 cu. in.

$$I = m \left(\frac{l^2}{3} + \frac{R^2 + r^2}{4} \right)$$

$$I_{cyl} = .916 \left(\frac{.188^2}{3} + \frac{1.546^2 + 1.362^2}{4} \right) = .985 \text{ slug ft}^2$$

$$I_{cone} = .574 \left(\frac{.387^2}{3} + \frac{1.16^2 + .98^2}{4} \right) = .362 \text{ slug ft}^2$$

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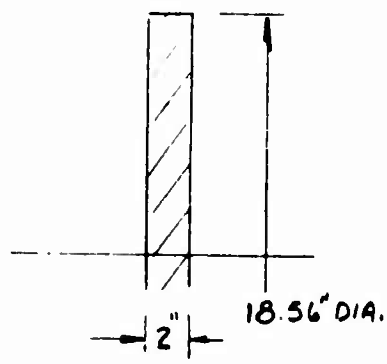
MOMENT OF INERTIA - INJECTOR

$$I = m\left(\frac{\ell^2}{3} + \frac{r^2}{4}\right)$$

$$= 1.83\left(\frac{.0834^2}{3} + \frac{.774^2}{4}\right)$$

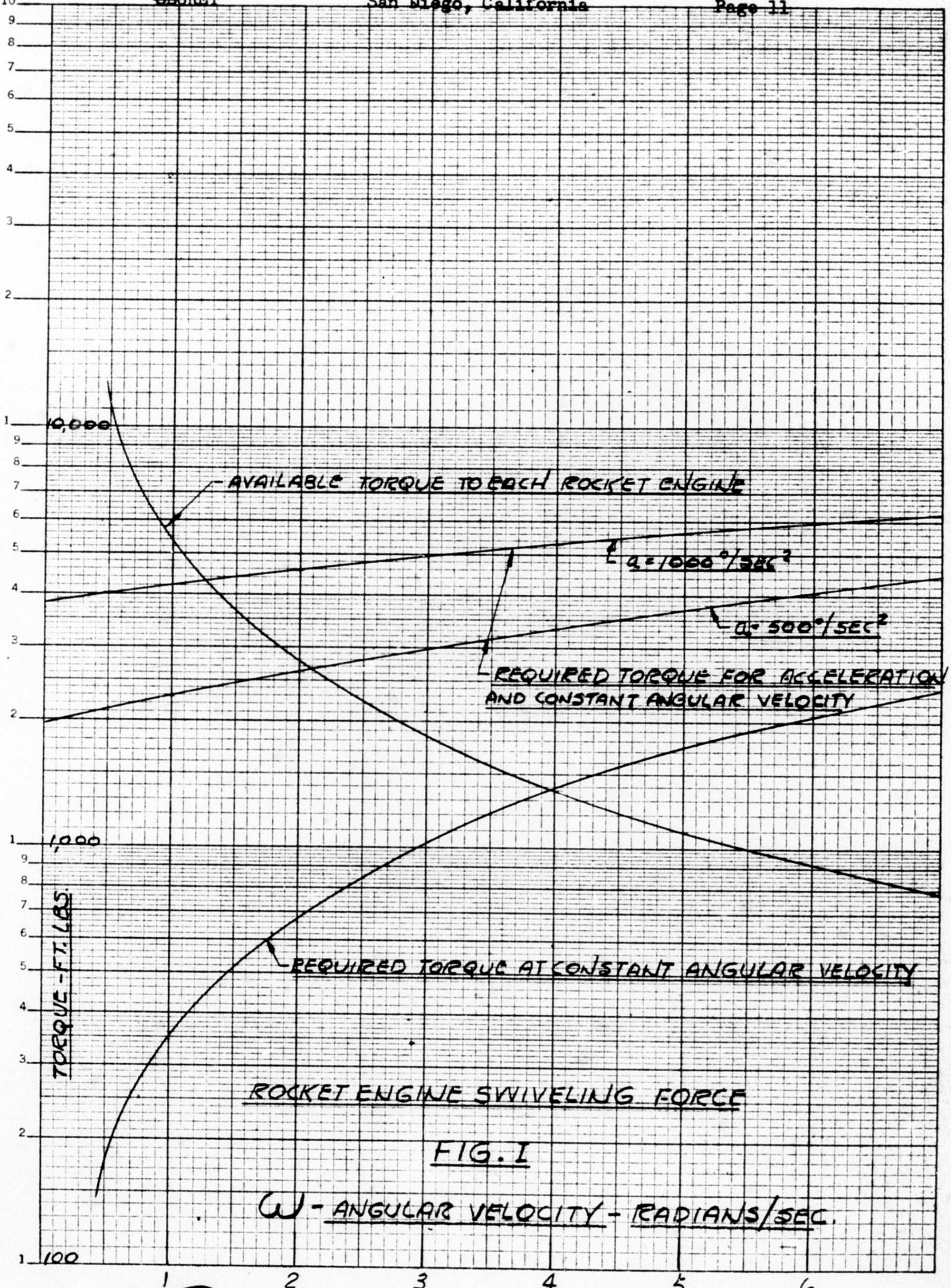
$$= .275 \text{ slug ft}^2$$



WEIGHT SUMMARY

HYDRAULIC CONTROL SYSTEM

		Wt-Lbs.
Hydraulic Pump		
New York Air Brake Co Model 67W, 27.5 gpm @ 2500 psi and 4500 rpm		24.0
Control Cylinder (4)		16.0
Servo Valve (4)		16.0
Filter		2.0
Reservoir (2 gal. capacity)		7.0
Shell	2.78	
Air Chamber	1.39	
Diaphragm	.78	
Fittings & Air Valve	.50	
Mounting	.75	
Filler Cap	.50	
Misc.	.25	
Accumulator (5" dia. size) Bendix S 100146		4.8
Lines and Fittings		21.78
Mounting		12.0
Heat Exchanger		4.0
Hydraulic Fluid MIL 5606, 4 gal @ 7.03 /gal		28.12
Misc.		5.0
Total Weight		140.8 lbs.



ROCKET ENGINE SWIVELING FORCE

FIG. I

359-71 KEUFFEL & ESSER CO. Semi-Logarithmic, 3 Cycles X 10 to the inch. 5th lines accented. MADE IN U.S.A.

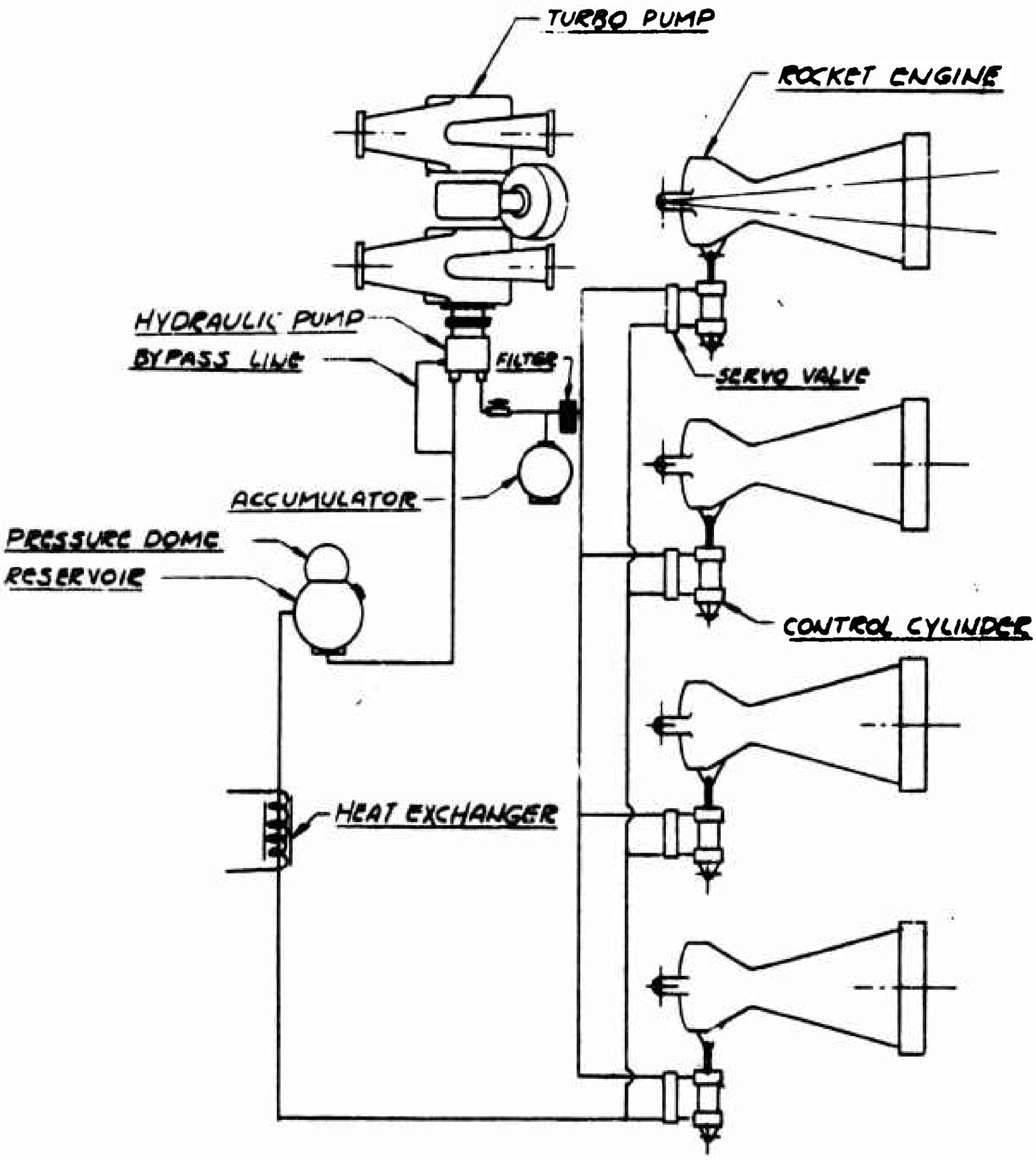
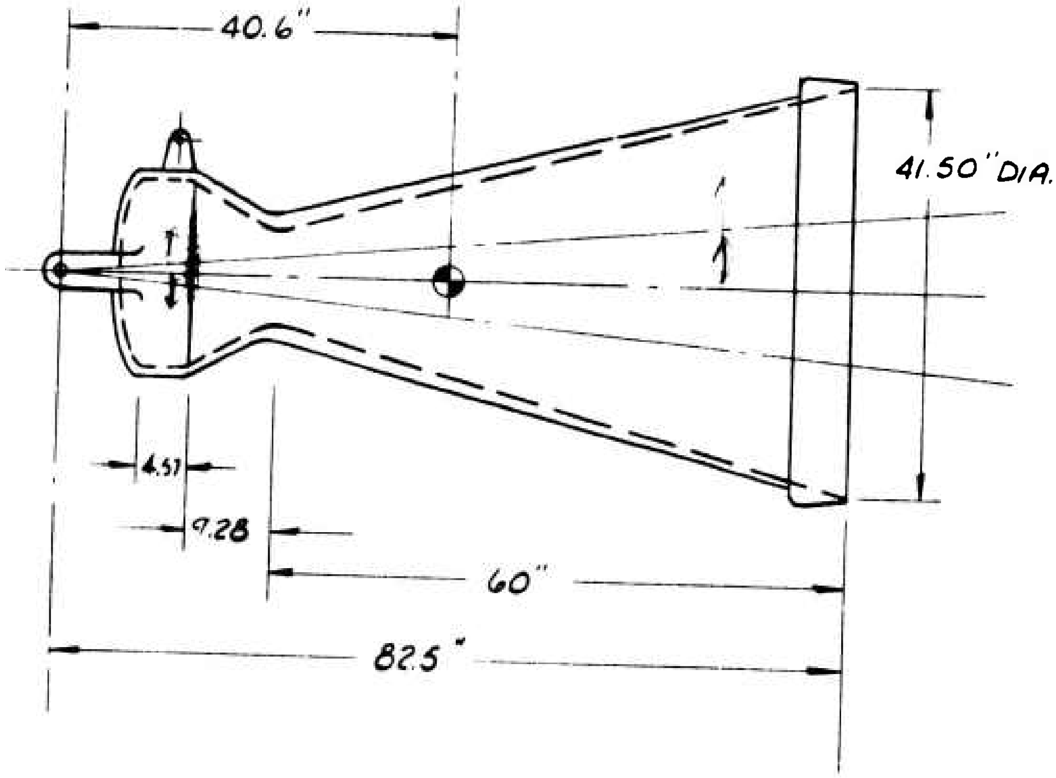
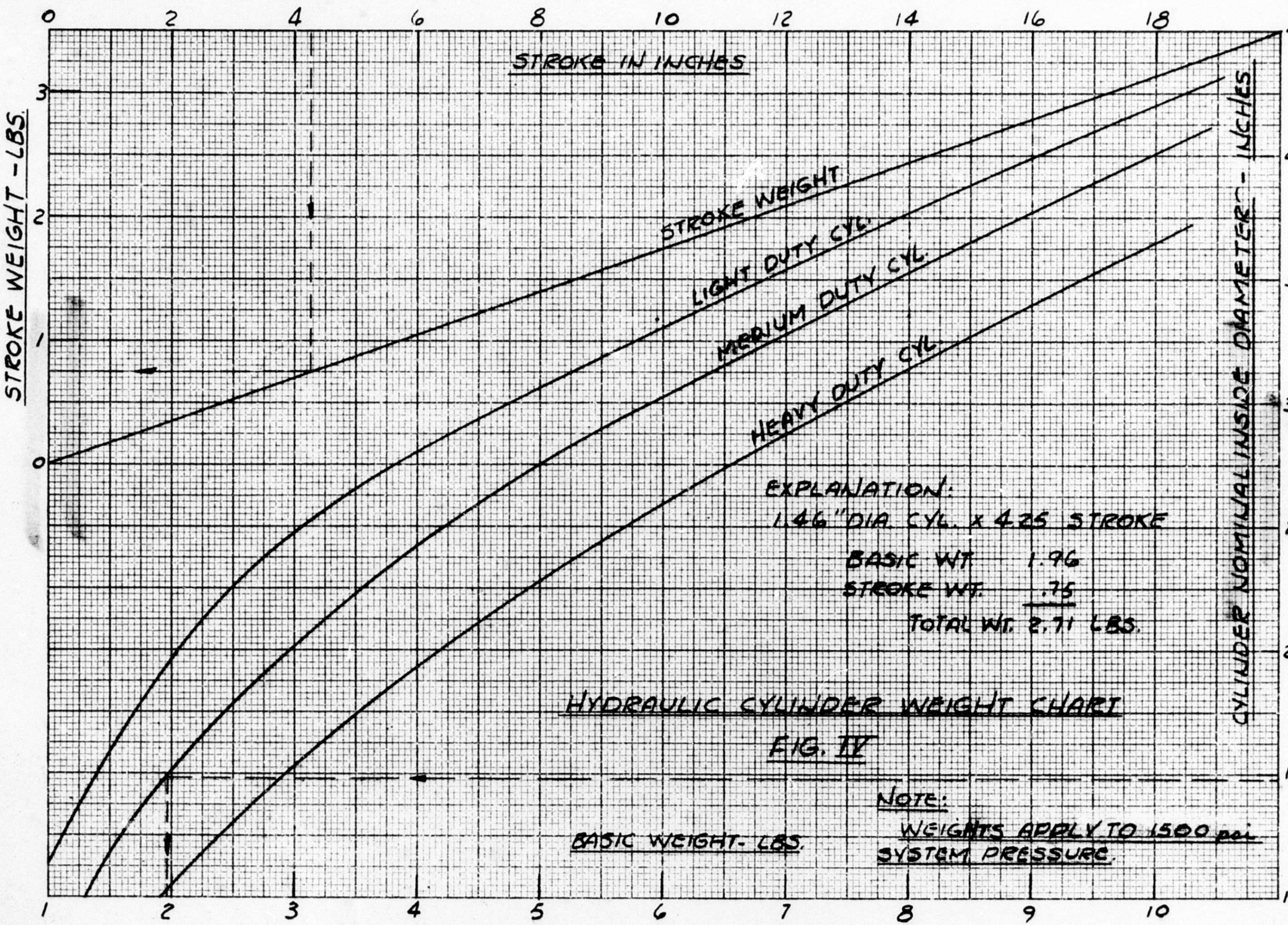


DIAGRAM - HYDRAULIC SYSTEM
FIG. II



ROCKET ENGINE OUTLINE
FIG III



HYDRAULIC CYLINDER WEIGHT CHART

FIG. IV

359T-11G KEUFFEL & ESSER CO.
10 X 10 to the ½ inch, 5th lines accented.
MADE IN U.S.A.